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DIRECT STEAM GENERATION IN PARABOLIC TROUGHS: FIRST RESULTS OF THE DISS PROJECT

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ABSTRACT

This article presents the latest experimental results of the European DISS (DIrect Solar Steam) project. The experiments are subdivided into steady state and transient tests. The goal of the steady state tests is the investigation of the thermohydraulic phenomena of the occurring two phase flow, whereas the transient tests are needed for the controller design. The experimental results are compared to simulation studies. Implications for the plant operation will be discussed.

INTRODUCTION

The direct steam generation (DSG) in parabolic trough collectors is a promising option for the improvement of the reliable parabolic trough technology for solar thermal electricity generation. Several open questions concerning the DSG process have to be answered before a commercial plant can be designed. These are among others the:

- operation of single and parallel rows under steady-state and transient conditions,
- start-up and shut-down procedures,
- strain of the absorber tubes due to transients and
- definition of the best operation mode

To overcome this lack of knowledge the DISS project has been initiated. The DISS test facility at the Plataforma Solar de Almeria (PSA) in Spain (Zarza and Hennecke 2000) is a full-scale solar steam generator with a length of 500 m and a maximum thermal power of approx. 2 MW. The design pressure at the outlet of the collector loop is 100 bar. The collector loop consists of modified LS-3[1] parabolic trough collectors, used to investigate and compare different process options under real operating conditions, as well as to develop and demonstrate appropriate components, control algorithms and operation strategies.

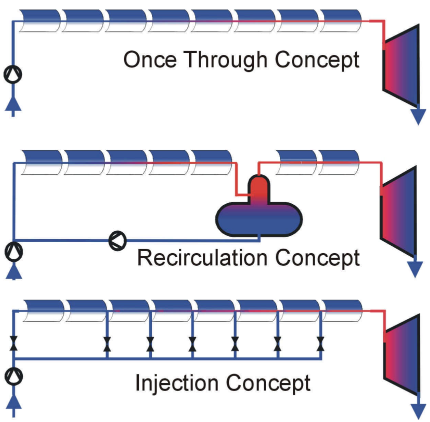

Fig. 1: Basic concepts considered for solar steam generation in parabolic troughs.

There are three different process options, the once-through, recirculation and injection concept (s. Fig. 1). The *once-through-concept* is the same as in a conventional Benson boiler. This concept is the most simple one but its controllability is to be investigated. The *recirculation-concept* is equivalent to a conventional recirculation boiler. It is the most secure concept but it is more expensive due to the additional separator and recirculation pump. An *injection-mode* collector loop is subdivided into different collector units. The series connection of all subgroups build the collector loop, where each subgroup consists of a collector, an injection and gauging equipment. The advantage of this concept is that the controllability of the process is expected to be better. The flexible design of the DISS test facility allows the investigation of the three different operation modes.

To investigate the DSG process, models describing the dynamic and steady state behavior of DSG have been

[1] The LS-3 (Luz System 3) is the collector used in the blocks VII to IX of the SEGS power plants. The LS-3 collector has a length of 99 m and an aperture width of 5.76m.

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developed and implemented in simulation programs (Steinmann and Goebel 1998). In this paper the preliminary results of the DISS project are compared to these simulation programs for the first time.

NOMENCLATURE

R	Recirculation Rate	[-]
l	Length	[m]
p	Pressure	[bar]

THE DISS PROJECT

Between December 1999 and November 2000 the facility (s. Fig. 2) has been operated for approx. 1500 hours. Within this period no problems with solar specific components like the absorber tubes or the ball joints occurred. Problems have only been provoked by conventional components like the recirculation pump and the thermocouples that detect the temperature distribution within the cross section of the absorber tubes (Zarza 2000). The numerous tests within this test period have demonstrated the feasibility of DSG in horizontal absorber tubes in principle. No critical situations have occurred neither during steady-state nor during transient tests.

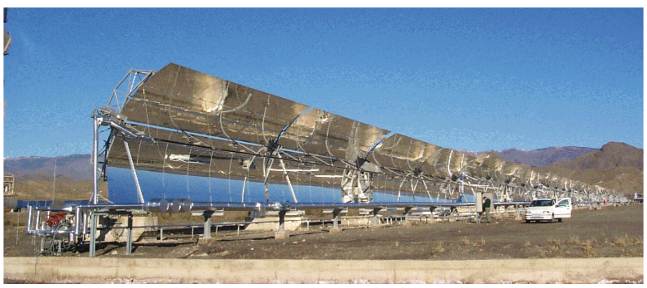

Fig. 2. Photo of the DISS test facility.

RESULTS

The test program contains steady state and transient tests for the different operation modes. The goal of the steady state tests is the investigation of the thermohydraulic behavior of the two-phase flow within the absorber tubes for different boundary conditions.

The main boundary condition for all operation modes is the pressure p at the collector outlet. All tests for the once-through and the injection concept are defined for 30, 60 and 100 bar.[2] Due to the operation problems of the recirculation pump at high pressure (Zarza and Hennecke 2000) the tests for the recirculation-concept are defined for 30 and 60 bar only. The second boundary condition for the once-through concept is the fluid temperature at the collector outlet. For a given Insolation this is equivalent to a certain mass flux at the collector inlet. The recirculation concept has two additional boundary conditions. The first is the recirculation rate R, that is defined as the ratio of the recirculated mass flux to the mass flux from the feed water pump (s. Fig. 1). The second is the relation between the length of the superheating section and the length of the evaporation section. In the case of the injection concept the number of injection coolers per collector row, the distance between them and the aimed steady state profile of the specific enthalpy along the collector loop are the additional boundary conditions.

The transient tests are subdivided into tests with and without the temperature control in operation. In the first step (without temperature control) the reaction of the test loop to different disturbances will be investigated (determination of the according transfer function). The most important tests of this test block is the investigation of the reaction to a shading of parts of the collector loop and the reaction to the controller output. The controller output for the recirculation concept is the mass flux from the feedwater pump. In the case of the once-through concept it is the mass flux at the inlet of the collector loop and in the case of the injection concept it is the mass flux through the injection coolers. The results of these tests are needed for the controller design. Within the subsequent test period the controllers will be checked and optimized.

The set up for the once-through and the recirculation mode in Fig. 1 can be supplemented by an additional injection cooler at the inlet of the last collector. This modification will improve the controller performance of these concepts significantly.

So far most of the tests for the once-through and the recirculation mode have been performed without a temperature control. The first tests in injection mode are scheduled to start at the end of 2000. The tests with an automatic temperature control are scheduled to start in spring 2001.

1. Steady State Tests

As mentioned before, the target of the steady state test is the demonstration of the DSG under real operating conditions and the investigation of the thermohydraulic phenomena. The design pressure of the test facility is 100 bar and the design temperature is 400°C. Figure 3. displays the outlet pressure and temperature versus local time for operation in recirculation mode measured on the 4th of July.

The operation pressure of the plant was kept constant at approx. 100 bar for nearly five hours. Shortly after 5 p.m. the plant was shut down immediately because of a failure of the recirculation pump[3]. Between 1 p.m. and 5 p.m. the outlet temperature is constant at approx. 370°C. In

[2] A higher operation pressure is advantageous from the thermodynamic point of view but it causes a higher mechanical strain and thus causes a higher construction effort.

[3] The recirculation pump is a conventional equipment and thus not related to the DSG process itself.

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the previous test the length of the superheating section was 75 m. If it would be extended to 100 m, the outlet temperature would reach the design temperature of 400°C. Nevertheless the design temperature has been reached within tests in once-through mode. This steady state test demonstrates the availability of the DSG in principle.

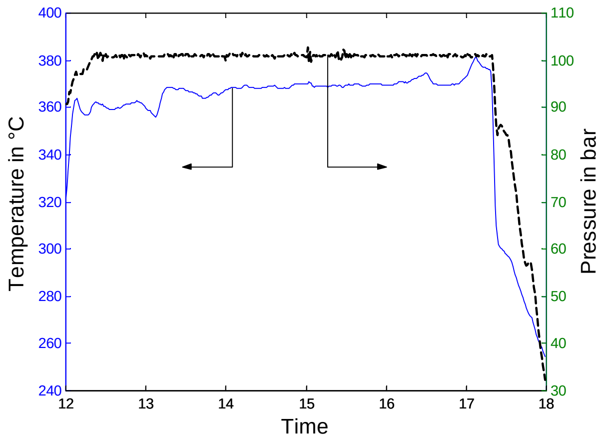

Fig. 3: Temperature and pressure of the fluid at the outlet of the collector loop measured on the 4th of July 2000. Operation in recirculation mode.

The simulation program used calculates the thermodynamic state of the fluid according to a energy balance and a pressure drop model along the collector loop with a step size of 1 m. Starting from the thermodynamic state the program applies empirical models for the determination of the flow pattern and the distribution of the heat transfer coefficient. The heat transfer coefficient and the assumed distribution of the irradiation on the outer surface are input for a FEM calculation of the temperature field in the cross section. The maximum temperature gradient is the difference between the highest an lowest temperature in one cross section.

The empirical models were derived from and validated by the results of numerous experiments from earlier DSG projects (Steinmann and Goebel 1998). Due to this extensive validation of the used models and the detailed calculation of the temperature field, this program is able to calculate most of the important parameters of a DSG collector loop. This makes it superior to other programs mainly based on models from literature or to that ones using rough simplifications of the system like the assumption of bulk temperatures for the absorber tube or mean heat transfer coefficients (e.g. Odeh et. al. 1998).

The low temperature gradient of less than 20 K in the preheating and superheating section (0 m – 425 m) indicates an annular flow in the absorber tubes. Due to the lower heat transfer coefficient of the steam flow in the superheating section (425 m – 500 m) the maximum temperature gradient reaches approx. 40 K, which is lower than the design value of 50 K. Figure 4 shows a good agreement between the simulated and the measured results.

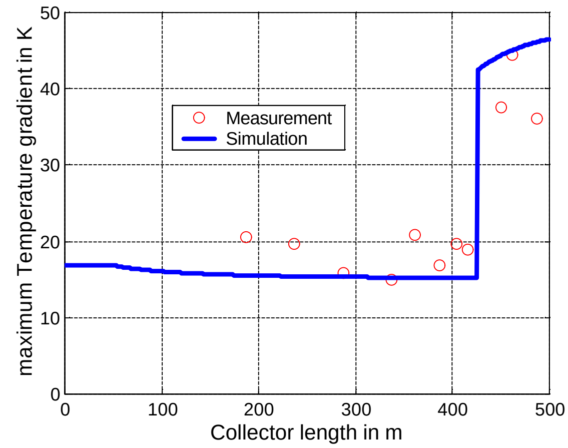

Fig. 4: Measured and simulated maximum temperature gradient along the collector loop for a test in recirculation mode at solar noon (p = 30 bar, R = 1).

High mass fluxes (high recirculation rates) guarantee a good cooling of the absorber tube and with that a safe operation of the DSG in horizontal absorber tubes. On the other hand high mass fluxes cause high pressure drops and with that a higher parasitic power consumption of the collector field. So it is desirable to identify a minimum mass flux that guarantees a sufficient cooling of the absorber tubes. For that purpose, the evaporator section of the DISS test facility has been operated with different recirculation rates. The maximum temperature gradient profiles for the investigated recirculation rates are displayed in Fig. 5. A recirculation rate of 0 is the same as the once-through concept.

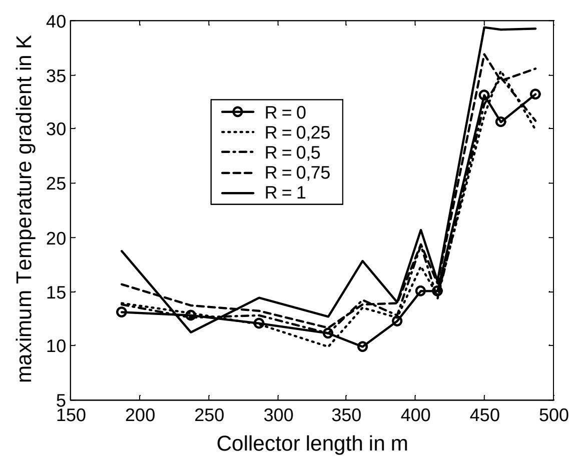

Fig. 5: Measured maximum temperature gradient profile for tests in recirculation mode for different Recirculation rates (p = 30 bar).

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In Fig 5. no explicit dependency between the recirculation rate and the maximum temperature gradient is observable. Thus indicating that a recirculation rate of 0.25 would guarantee a sufficient cooling of the absorber tubes. A Recirculation rate of 0 would also guarantee a sufficient cooling, but in this case the recirculation-concept would turn into the once-through-concept with its specific problems, explained in the next section.

All the tests used for this comparison have been performed between noon and 3 p.m. local time. So all tests are subject to a similar irradiation angle, that represents bottom heating which causes the smallest temperature gradient. But nevertheless further simulation studies outline that the low recirculation rate is sufficient.

The measured pressure profile as a function of the recirculation rate is displayed in Fig. 6. The pressure drop is calculated by the well known model of Lockhard-Martinelli with the extension of Thom (1964). The graph indicates, that a reduction of the recirculation rate from 1 to 0.25 would decrease the overall pressure drop and with that the power consumption of the pumps by approx. 32%.

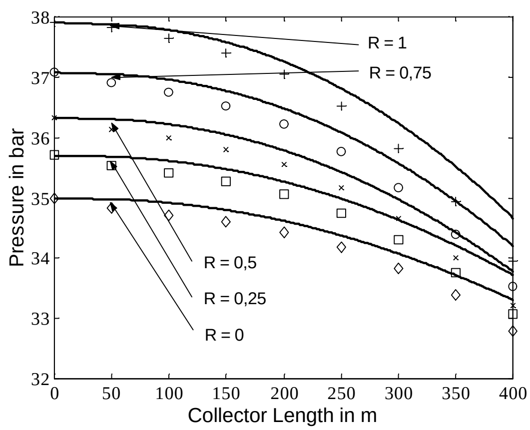

Fig. 6: Measured and simulated (-) pressure profile along the collector loop for different Recirculation rates and a steam mass flux of 0.4 kg/s (*p* = 30 bar).

As displayed in Fig. 6. the predicted pressure drop is smaller than the measured. One reason for this mismatch is that so far the model doesn't consider the U-bends used in the test facility every 50 m.

The reduction of the recirculation rate has a further advantage. The recirculation concept requires a separator at the end of the evaporator section for the phase separation of the two phase flow. So far a large separator vessel is used. Due to the high working pressure this vessel has a wall thickness of several centimeters (depending on the volume), thus representing a high thermal inertia, that causes a longer start-up time. The significant reduction of the recirculation rate leads to higher steam fractions. For higher steam fractions it might be possible to substitute the separator vessel by alternative, smaller separator concepts like commercial cyclone separators or something similar. These concepts have a lower thermal inertia and could be much cheaper (s. last section).

The once-through-concept is a competing operation concept, that has the most simple design and with that the lower investment. If it turns out that the operation of the once-through mode is safe and reliable, it would be the first choice. Figure 7 displays the steam temperature profile at the collector outlet and of the maximum temperature gradient profile in the cross section at the location of 404 m for a day with perfect weather conditions (clear sky) and a constant mass flux at the inlet of 0.53 kg/s.

Due to the constant mass flux at the inlet the outlet temperature follows the march of the direct solar radiation, except the period between 1 p.m. and 2 p.m.. Here a small variation of the inlet mass flux of less than 3% causes a decrease of the outlet temperature of about 50 K. Since the specific heat capacity of the steam is greater for higher pressures this effect will be smaller for higher pressure.

One specific problem of the once-through concept is the variation of the end of the evaporation section that causes high temperature gradients in the absorber tube, that may exceed the limits of the material. This phenomenon has been investigated in detail in previous theoretical studies (Eck and Steinmann 2000). Figure 7 shows the variation of the maximum temperature gradient in a cross section at a fixed position (404 m).

Before 2 p.m. the temperature gradient is less than 20 K which indicates an annular flow (see the comments to Fig. 4 and 5). Between 3 p.m. and 3:45 p.m. the gradient is approx. 35 K, which indicates a pure steam flow[4]. Between 3:45 p.m. and 5 p.m. great temperature fluctuations caused by a persistent variation of the end of the evaporation section can be observed. These temperature transients of approx. 5 K/s will cause a high thermal stress in the absorber tube that can reduce the durability of the absorber.

The present results of the steady state tests prove the availability of DSG in recirculation mode in horizontal absorber tubes. Up to now no critical situations occurred. This result complies with earlier theoretical studies (Steinmann and Eck 2000) that predicted no critical situations for the steady state operation of DSG in recirculation mode. The operation performance, in terms of constancy of the outlet temperature and stress problems at the end of the evaporation section[5], of the recirculation mode shows better results compared to the once-through mode. Although this statement is based on the experience

[4] Another explanation could be the change of the flow pattern of the two phase flow. But the observation of the fluid temperature at the position of 400 m indicates a pure steam flow (the fluid temperature is greater than the saturation temperature of the according pressure).

[5] For the recirculation concept the end of the evaporation section is fixed to the position of the separator.

of more than six month of operation it has to be regarded as preliminary.

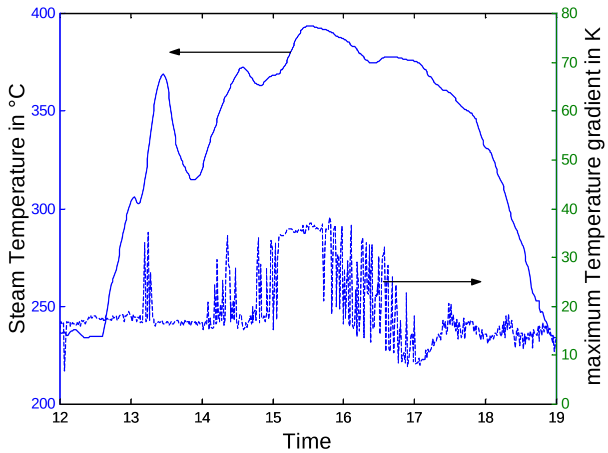

Fig. 7: Measured steam temperature at the collector outlet and the maximum temperature gradient in the cross section at the position of 404 m for a test in once-through mode (p = 30 bar).

2. Transient Tests

The target of the transient tests is the investigation of the dynamic behavior of the collector loop. The information gathered are needed for the design and optimization of the controller. For the controller design transient tests are performed without the use of a temperature control. Later tests with the use of the temperature control are used for the optimization. The control scheme for the DISS facility is described in the yearly report of the DISS project (DISS 1999).

The most important disturbance of the system is a variation of the direct radiation. Figure 8 displays the measured and simulated outlet temperature after a temporary shading of the two collectors of the superheating section for a test in recirculation mode. First the 10th (425 m < l < 450 m) collector was defocused for approx. 2000 s, later the 11th (450 m < l < 500 m) collector was defocused for approx. 1800 s. Due to the greater length of the 11th collector the temperature deviation at the loop outlet caused by the shading of the 11th collector is higher than the deviation caused by the shading of the 10th collector. It is obvious that the experimental data set and the according simulation produce very similar results.

The dynamic behavior, which is in this case (shading of a superheating collector) the same as for an once-through collector loop, is similar to the behavior of an nth order linear system. This conclusion is in agreement with the results of earlier lab scale studies (Eck and Geskes 1998). From the point of view of the control theory this behavior is non-problematic. Thus a simple PI-controller might be sufficient for the temperature control of a superheating collector.

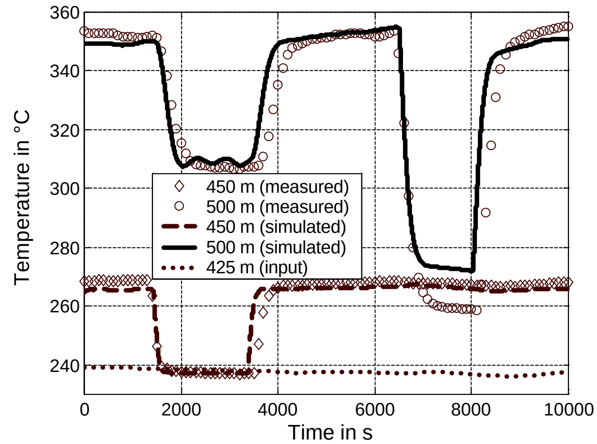

Fig. 8: Measured and simulated steam temperature after a temporary shading of the 10th and 11th collector for a test in recirculation mode (p = 30 bar).

The situation changes if a collector of the evaporator section is shaded. Figure 9 and Fig. 10 show the measured results for one test in recirculation mode.

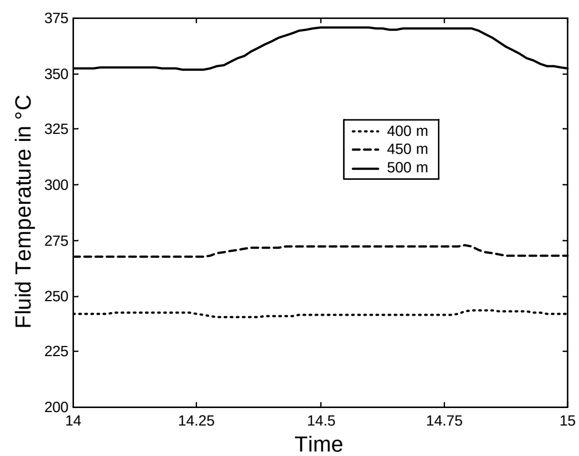

Fig. 9: Measured fluid temperatures after a temporary shading of the 1st collector for a test in recirculation mode (p = 30 bar).

During this test the first collector (0 m < l < 50 m) was shaded for approx. 30 minutes (s. Fig. 10). In contrast to the shading of a superheating collector the fluid temperature at the collector outlet increases. The reason for this behavior is the reduced steam production of the evaporator section. Assuming a constant liquid level in the separator the decreased steam production causes a smaller steam mass flux in the superheating section (s. Fig. 10). Since the radiation in the superheating section is constant the fluid temperature in the superheating section increases (s. Fig. 10). The fluid temperature in the evaporator section

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(temperature at 400 m in Fig. 9) decreases slightly due to the smaller pressure drop in the superheating section (the outlet pressure is constant) causing a lower pressure in the evaporator and therewith a lower saturation temperature of the fluid. Nevertheless, the dynamic behavior of the system is as non-problematic as that of the superheater section.

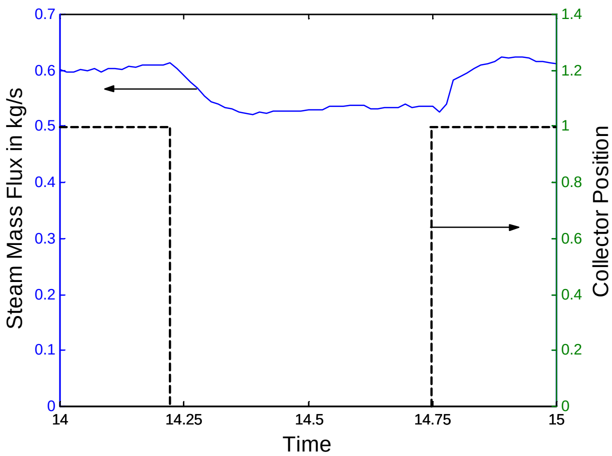

Fig. 10: Measured steam mass flux and the position of collector 1 (0 = defocused) for the test of Fig. 8.

The situation is different if the first collector of a once-through driven collector loop is shaded. Here the steam temperature at the collector loop outlet increases temporary to nearly 400°C and than decreases to its new steady state value of approx. 270 °C (s. Fig. 11). The outlet temperature would have exceeded the 400°C limit if the 11th collector had not been defocused shortly for safety reasons. The later refocusing of the first collector shows the same behavior with an opposite sign. This dynamic behavior is the result of the superposition of two effects.

The first effect is the temporary decrease of the steam mass flux to 60% of its steady state value (s. Fig. 12), due to a decrease of the specific volume at the outlet of the first collector caused by the lower heat input. The lower specific volume causes a lower flow velocity thus causing a lower mass flux at the collector outlet, where the specific volume of the steam changes not as much as that of the two phase flow. This temporary decrease of the steam mass flux causes a temporary increase of the steam temperature.

The second effect is the remaining decrease of the temperature at the outlet of the first collector (l = 50 m) during the shading (s. Fig. 11). This effect is observable as a decrease of the inlet temperature (enthalpy) of every downstream collector, thus causing the remaining decrease of the outlet temperature (enthalpy) of the according collector. Since this disturbance has a much lower velocity of propagation, this effect is observable after the elapse of the dead time of the flow system.

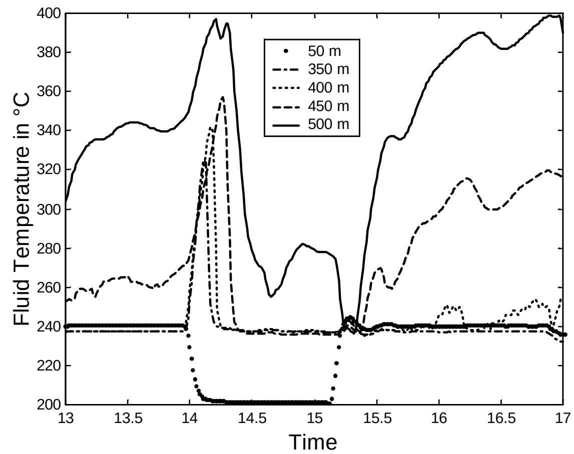

Fig. 11: Measured fluid temperatures after a temporary shading of the 1st collector for a test in once-through mode (p = 30 bar).

This test points out three specific disadvantages of the once-through-mode. The first problem is the very sensitive respond to any disturbance (variation of mass flux or irradiation; see also Fig. 7). The shading of the first collector causes a very high variation of the outlet temperature between nearly 400°C and 240°C compared to the variation of less than 20 K for the recirculation concept for the same disturbance (s. Fig. 9).

The second problem is the initial variation of the outlet temperature into the opposite direction to the later steady state value after the irradiation disturbance. In control theory such systems are called non-minimum phase system. The achievable controller performance of these systems is limited. The controller tests have to show whether simple PI-controllers can cope with this behavior or more sophisticated control strategies are necessary[6].

The third problem has already been mentioned, it is the variation of the end of the evaporation section. An clear example for this problem is the collector position at 450 m described by its fluid temperature in Fig. 11.

In the initial steady state a pure steam flow exists at this location (the temperature is higher than the saturation temperature of approx. 240°C). When the mass flux decreases the temperature increases until it reaches 350°C. But suddenly the fluid is cooled down to its saturation temperature, indicating the presence of a two phase flow. Since the fluid temperature is coupled to the absorber temperature the temperature gradient in the absorber is similar to that in Fig. 11. This transient of 100 K in a few seconds will certainly cause high thermal stresses in the tube and limits the lifetime expectancy of the absorbers.

[6] This effect would be enforced if an additional feedforward control is used. The feedforward control would react on the reduction of the radiation with an according further reduction of the mass flux at the inlet.

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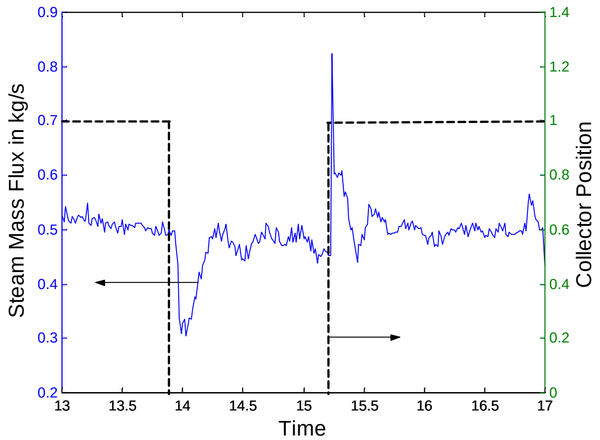

Fig. 12: Measured steam mass flux at the collector loop outlet and the position of collector 1 (0 = defocused) for the test of Fig. 11.

In a former theoretic study (Steinmann and Eck 2000) it was shown that the stress in the tubes exceed the limits of the material in this case. Almanza (1999) has investigated the influence of the variation of the evaporation section in experimental studies using a parabolic trough collector with an aperture width of 2.5 m and a length of 14.5 m. He observed a bending of the absorber tube causing the destruction of the glass envelopes. As a solution of this problem he suggests the insertion of a copper tube into the absorber tube providing an improved heat transfer in the cross section that reduces the stress to an accepted level. The economy of this solution seems doubtful. Lippke (1996) investigated the dynamic behavior of the once-through-concept, but didn't consider the variation of the end of the evaporator section.

It has to be stated that the two tests are not identical. The separator used in the recirculation concept represents a buffer that damps mass flux transients by a variation of the liquid level, that is not constant during the test, and with that damps the temperature peaks. But nevertheless this is a specific feature of the recirculation concept that depends on the size of the separation drum.

In a commercial plant operated in once-through-mode an injection cooler would be installed in front of the last collector in each line. If a modified LS-3 collector is used this would mean 100 m in front of the collector loop outlet. This will decrease the variation of the outlet temperature significantly. But nevertheless the problem with the end of the evaporation section remains. Therefore an operation mode where the end of the evaporation section is fixed (recirculation concept) or where it is possible to keep it within a small range (poss. the injection concept or a simplified recirculation concept) is highly desirable.

SUGGESTIONS FOR SIMPLIFIED SEPARATORS

In the previous section it was pointed out that it is important to fix or restrict the region of the end of the evaporation section. So far a conventional separator drum is used at the DISS test facility with the described disadvantages (expensive, high thermal inertia). Therefore it is worthwhile to look for alternative solutions.

One possibility could be the insertion of a commercial cyclone separator (s. Fig. 13). These kind of separators are used for the phase separation of two-phase-flows with high void fractions ($\dot{x}$ > 0.9), e.g. to protect steam turbines against water droplets. In this case there are many open questions, like the degree of the phase separation for lower void-fractions and during transients, the influence of the lower system volume and the system controllability, that have to be answered in future investigations.

The most simple solution might be a simple T-junction (s. Fig. 14). From process engineering it is well known that T-junctions cause an unintentional phase separation in two phase flow pipe networks (Azzopardi and Hervieu 1994). It is self-evident to use this effect in the present case. In future investigations it has to be proven which geometric and thermodynamic parameters affect the degree of the phase separation and how they should be chosen to maximize the degree of separation.

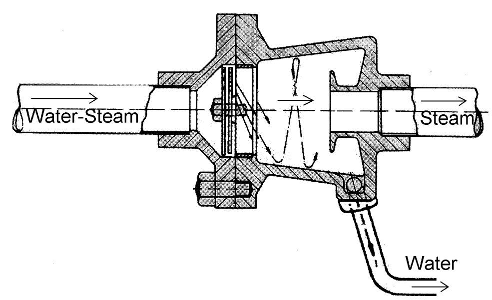

Fig. 13: Schematic design of a cyclone separator (in the style of (ASA 2000))

Figure 14 shows one poss. schematic design of one collector loop with a T-junction as a phase separator[7]. In this case the T-junction is oriented in an upright position (other orientations are conceivable). Here the phase separator is combined with an inclined recirculation pipe. The inclination leads to a better volume to height ratio which offers the possibility to use the differential pressure in the recirculation line as the control signal for the recirculation pump. In a commercial collector field one recirculation pump will be used for several collector loops or even the complete collector field.

The degree of the phase separation of these two outlined possibilities will be less than 100%, but

[7] The schematic design in case of the cyclone separator would be similar.

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nevertheless a partial phase separation could reduce the strain of the absorber tubes caused by the variation of the end of the evaporation section.

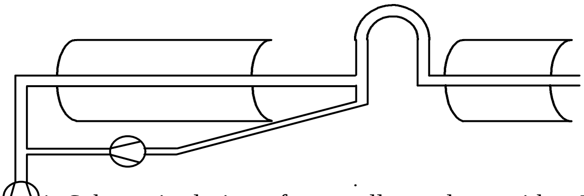

Fig. 14: Schematic design of one collector loop with a T-junction as a phase separator

As mentioned in the previous section every collector loop of a once-through collector field will require at least one injection cooler. The good system performance of the recirculation concept enables the use of only one injection valve for several collector loops or even the use of a by-pass between the main feedwater and steam line. Therefore the main advantage of the simplified phase separators would be a significant reduction of the investment costs, thus decreasing the difference in investment costs between the once-through and recirculation-concept. If the utilizability of these systems could be proven, the recirculation concept would not only be the safest but also a well-priced operation mode.

CONCLUSIONS

Experimental results of the DISS project performed at the Plataforma Solar de Almeria are presented. These results show clearly the supremacy of the recirculation-mode over the once-through-mode in terms of the thermohydraulic stability and the strain of the absorber tubes. The experimental results are compared to simulation results of the steady state and transient behavior of the direct steam generation in parabolic troughs. The comparison of the results show a good agreement. These programs will be used for the controller design and assessment of the different operation modes.

So far (as of Nov. 2000) no experiments in injection mode nor with an automatic temperature control have been performed, therefore a final evaluation of the three concepts is not possible. In further experimental studies the once-through-concept has to prove its controllability and the injection and recirculation-concept have to prove their potential of further improvements. An improvement of the injection mode will be the minimization of the number of injection coolers and that of the recirculation-concept will be the simplification of the separator. Beyond it the injection-concept has to prove its thermohydraulic stability.

Suggestions for the overcoming of the main disadvantage of the recirculation-mode, the complex design, are presented. Further investigations have to show the efficiency of these simplified separator concepts.

ACKNOWLEDGMENTS

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